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ELECTRON BEAM MICROFABRICATION SYSTEMS.(U)

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Electron Beam Microfabrication Systems

by
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and
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APRIL 1977

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Naval Weapons Center
CHINA LAKE, CALIFORNIA 93555

Naval Weapons Center

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FOREWORD

This report covers a survey of electron beam microfabrication systems. Work was authorized under contract No. 5525-6880-76. Work on this survey was performed between January 1976 and January 1977. This is a final report.

This report was reviewed for technical accuracy by G. Turner.

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(U) This report is a survey of electron beam microfabrication systems reported in the open literature as of 1 January 1977. Two categories of systems are identified based upon either beam scanning or beam projection as the image forming mechanism. In general, beam scanning systems provide higher resolution and accuracy while beam projection systems are used to obtain a larger throughput.

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INTRODUCTION

Since the late 1960s, electron lithography has gained rapid acceptance as a technique of great potential for fabricating large-scale, high-resolution integrated circuits (References 1-4). Requirements for devices with faster switching frequencies and higher packing densities have created a need for higher resolution patterns (less than 1.0 μm), accompanied with higher yield. Pattern delineation using focused electrons has been shown to be a useful technique for producing features of less than 0.1 μm. Other advantages offered by electron lithography are direct computer-controlled pattern generation, precise line width control of conventional size features (useful in master mask production), and lower defects in the finished product. Electrons can be imaged to form either a pattern or a small point and can be deflected and modulated with speed and precision by electrostatic or magnetic fields. Their energy and dose can be controlled precisely. Special electron-sensitive resists have been developed which have suitable processing characteristics and which can be effectively exposed at the level of radiation that can be conveniently generated in practical electron-beam machines. As a consequence, electrons can be used in a number of ways involving either beam scanning to generate patterns directly on the substrate, or electron imaging from special masks.

Various pattern generation techniques for electron beam systems have been developed and reported in the literature. The purpose of this report is to review those techniques.

BEAM SCANNING SYSTEMS

Electrons from a source can be formed into a pencil-like beam that can be deflected over an electron resist-coated substrate and modulated to draw a desired pattern. The beam can be imaged to a submicrometer spot with sufficient current to locally expose the resist in less than 10^{-7} second. Since up to 10^{-11} spots are typically required, this high speed is important. Positioning 10^{-11} spots accurately requires a precision of about one part in 10^6 along each coordinate axis. This places inordinate demands on the electron deflection system. The practical range of deflection is limited to a few millimeters because of (1) the difficulty of digital-to-analog (D/A) conversion with stable accuracy, (2) nonlinearities in the electron deflection system and uncertainties in the surface position of the substrate due to wafer bow which limit the allowable angular deflection, and (3) electrostatic and

magnetostatic perturbations which limit the working arm. Since this is less than the diameter of a substrate, a mechanical table is used to move the substrate to allow the full substrate area to be exposed.

Ensuring that the relative position of the beam and table is within the required accuracy has led to two divergent approaches. In each, the electron column is used as a scanning electron microscope (SEM) to locate registration features on the substrate for realignment purposes. In one approach, realignment on separate registration marks is accomplished for each table position. In the other, laser interferometers are used to control the precision of table motion. After the initial registration, only occasional registration is used on a single mark to guard against beam drift. Random or raster scan strategies and a variety of deflection field sizes, pattern information processing systems, and mechanical table arrangements have been used in an effort to improve system accuracy and throughput.

It has been demonstrated that an electron beam pattern generator can make chromium master masks with better accuracy, better line width control and edge quality, lower deflection density, and lower cost and faster turnaround than an optical pattern generation system of very high quality. This applies to state-of-the-art as well as normal master masks. The usefulness of beam scanning systems for direct device processing is not yet too clear. The beam scanning system can provide at least as good resolution, realignment accuracy, and low deflection density as the best of alternate systems, e.g., electron projection and X-ray exposure systems, as the beam scanning system would be used to make the mask for the other systems. However, because the scanning electron beam system forms the wafer pattern in a serial fashion, exposure times are inevitably much greater than those of the competing technologies involving a masking operation with its parallel transfer mode. Evidence is developing that the beam scanning exposure system is economical for fine-line devices of high value where lithographic quality is critical, such as in microwave transistors. It is expected, but has not yet been demonstrated, that direct exposure will prove to be economical for producing conventional large-scale integrated circuits because of their high yield and large number of smaller circuits that can be made per wafer, their great speed, and lower power consumption. These factors would tend to overcome the higher machining costs and longer exposure times as compared to the present optical exposure systems.

The early electron beam exposure systems were made by a "flying-spot" scanner (References 5-13). The scanner consists of a high-resolution CRT (more than 3,000 lines over the pattern area) generating a line raster that is projected through a lens onto a mask. Light transmitted through the clear areas of the mask falls on a photomultiplier, and the resulting signal is used for blanking the electron beam. This system requires a high-definition mask that is prepared by photographic techniques. The flying-spot scanner also suffers from limited resolution because of the CRT.

The use of a computer coupled to a SEM for controlling the electron beam offers many advantages over the flying-spot scanner. Patterns are first generated as software statements. These statements, in turn, generate beam deflection and blanking information in digital form. The digital information is then outputted to D/A converters from which analog deflection and blanking signals are used to write the patterns directly on the substrate without the use of a mask. Therefore, the limit of resolution within a given area of the substrate is determined by the number of bits that the D/A

converters can handle, the overall stability of the electron beam system, and the electron resist resolution capability In some systems the electron beam scans only the areas to be exposed (vector scan); thus, time is not wasted by scanning blank areas. Also, the computer can be used to form other functions, such as processing of the data and alignment. The basic requirement of a digital pattern generator is a pair of D/A converters, one each for the x- and y-scan direction. D/A converters coupled to a pair of counters and fed from a suitable information reader form the basis of a digital control system. In general, a scanning microfabrication system consists of three main parts: computer, electron column and specimen stage, and power supplies. The electron column and specimen stage, in general, consists of the following units:

1. Electron optical column consisting of an electron gun and condensing lenses.
2. Electron beam deflector unit to carry out the electromagnetic deflection of the beam.
3. Detector unit for registration.
4. Work stage to support and move the substrate.
5. Work stage shift system to make the x-y shifts by using stepping motors and feed screws.
6. Work stage detector unit to measure travel of the workpiece, usually by means of a laser interferometer, and feed the measured value to the computer.
7. Evacuation unit to maintain the right pressure in the system.
8. Operation panel with controls for beam intensity and focus.
9. Scanning control units to control the deflection and blanking of the beam according to instructions from the computer.
10. CRT monitor to evaluate patterns and to display scanning electron microscope images.

Lithography systems intended for use in fabricating complex microsize structures must be capable of performing registration between exposures of successive levels. Several kinds of alignment marks and beam-serving methods have been discussed in the literature by various authors. One of the earliest methods was demonstrated by Wells *et al* (Reference 5) and was based on sensing the electron-beam-induced response of a p-n junction for aligning an adjacent gate exposure. Other methods have employed oxide pedestals (Reference 7), moiré fringes (References 14-16), high-atomic-number alignment marks (References 17 and 18), silicone steps (Reference 19), and laser interferometers (References 19-22). Electron beam lithography for line widths of 0.5 μm and less often require an alignment accuracy of 0.1 μm or better. This level of precision demands very accurate scanning electron microscopy of the alignment marks, digital processing, and fast positional control feedback via a digital computer Accurate high-speed, computer-controlled, electron beam alignment requires alignment marks that have high signal contrast for detectability, high signal-to-noise ratio for rapid data acquisition, and high edge acuity for precise location.

Registration can be considered on a wafer basis (a one-time registration), flat and undistorted substrates, and exact stage motion during the step-and-repeat process by relying on extreme system stability. Or it can be considered on a chip-by-chip basis making fine corrections at each site. The former system can have a special mark region, and considerable time can be tolerated to achieve

registration. The latter system is usually required to complete a registration cycle in a time that is short compared to the sum of pattern write time and stage chip-to-chip step time.

At present there are basically three types of electron sources being used in the scanning systems: tungsten thermionic emitters, lanthanum hexaboride cathodes (LaB_6), and field emission cathodes. Tungsten thermionic cathodes are not well-suited for microfabrication due to the lower brightness levels achievable and the relatively short lifetimes. LaB_6 cathodes can be operated at higher brightness levels, but they still suffer from short lifetimes. Field emission cathodes have intrinsically very high brightness levels with very long lifetimes, but there are problems with emission stabilities with large beam currents.

In the following paragraphs a review of computer-controlled scanning systems is given, with emphasis on their strategy and important features relative to other systems.

HUGHES RESEARCH LABORATORIES, MALIBU, CALIF. (References 17, 18, and 23-26)

A computer-controlled electron beam exposure system has been developed that uses an electron beam of small diameter. In this system a hybrid approach is employed for pattern generation utilizing both digital and point-by-point techniques. Low-resolution patterns are exposed using analog ramps with digital endpoint definition and a large diameter electrom beam. This complementary approach permits the designer to minimize the performance required of individual components for a specified level of overall system performance. The system is designed to operate in the line width range of 0.1 to 1.0 μm. The critical aspects of this type of pattern generator is the performance of the comparators and the degree of registration between the two types of patterns.

The SEM used is a Cambridge Stereoscan Mark IIA instrument equipped with a tungsten hairpin filament source, beam blanking, electrical scan rotation, a 1- by 2-inch (25- by 51-millimeter) travel, x-y stage, and the capability of accepting external deflection and blanking signals. The computer is a Varian 620/I microcomputer with 16,000 words of core memory. The central processing unit has capabilities for power failure restart, real time dock, hardware multiply-divide, extended addressing direct memory access, and interrupt function. The peripherals consist of an electrostatic printer-plotter, two magnetic tape transfers, a disk memory display unit, paper tape equipment, a digital voltmeter, two teletypes, and a controller interfacing the computer to the SEM through which digital information is outputted to 15-bit D/A converters.

The system operates in several modes: (1) generation of software for process control, (2) generation of patterns, (3) pattern writing, (4) diagnostic data input, and (5) calculation and data processing. The registration method is based on the collection by a detector (a high-gain collector) of high-energy back-scattered electrons that are generated on the substrate from high-atomic-number alignment marks (References 17 and 18). The pattern field consists of four slightly overlapping scan fields. This multiple-scan-field approach permits a high-resolution pattern to be written over an area approximately four times larger than deflection aberrations would permit. After the exposure of a chip

is completed, the stage is moved mechanically to the location of the second chip where registration starts again (exposure on a chip-by-chip basis). An automated stage movement using a laser interferometer will be employed in the near future.

BELL TELEPHONE LABORATORIES, MURRAY HILL, N.J. (References 21, 22, and 27)

An electron beam exposure system built at BTL has proven to be practical and economical for generating high-quality fine-featured integrated circuit masks. It is also capable of exposing patterns directly on resist-coated silicone wafers (References 21 and 22). The system, which also works from patterns described in computer software, is based on a different strategy for integrating a scanning beam and a moving table into a lithographic exposure process. It is a practical system designed to meet the important current needs for moderate resolution (line widths of approximately 2 μm) rather than to illustrate the ultimate limits of electron beam capability. The strategy employed by the system to exposure masks or wafers is a form of raster scan wherein the scan lines are generated by periodically deflecting the beam over a line of limited length (128 μm); the full substrate area is covered by moving the substrate continuously under the beam while the beam is scanning. The electron beam is focused to a 5-μm-diameter spot on the resist film covering the substrate. The beam is modulated on and off at 100 megahertz as it scans across the boundary locations of pattern features. The exposure time on each spot is 100 nanoseconds. A laser interferometer continuously monitors the lateral position of the substrate. When the actual path of the substrate deviates from the desired path by 0.03 μm or greater, signals are sent to the beam deflector to produce a compensating beam deflection. Thus, an absolute pattern accuracy is defined by the interferometer over the entire substrate surface independent of uniform table motion. The pattern description of a chip is dissected into stripes of fixed width corresponding to the fixed width of the beam scan line. The features within one stripe are then read into a core memory to form an array of bits geometrically similar to the pattern of the stripe. To expose the stripe, the core memory is read serially, causing the beam to be modulated in synchronism with the raster scan. Since there is an array of many identical chips on the substrate, the memory is read repeatedly to expose an identical stripe on each similar chip in the array. When this is done, a second stripe is stored in the core, and the modulation commands are read out to expose, at each chip location, the second stripe of the pattern continuous with the first. The process continues until the last stripe of the chip pattern has been exposed, at which the substrate exposure is completed. The registration is made by exposing three marks during the first-level lithography; and during subsequent patterning steps, these marks are located. The chip pattern and array descriptions are then adjusted through the software and electronic interfaces so that the new pattern and the previously exposed patterns will match precisely at the three marks. The electron-beam exposure system uses a simple method of mark detection. When the beam crosses the boundary of a mark, more electrons scatter away from the substrate, and a decrease in current collected by the substrate is observed. The net current to

the substrate, modulated in time by this effect, is amplified and supplied to the computer. This alignment procedure is made at the beginning of the exposure of each level (once for the entire substrate) and during the exposure. Registration is checked every 5 minutes by using the electron column as an SEM to locate a registration mark.

The modified electron optical column was originally a component of a Cambridge Stereoscan S-4 SEM. A Data General 800 control computer is used with custom hard-wired logic and dedicated microcomputers to interface and control the various parts of the system. A large disc file, card reader, and tape deck facilitate handling the programs and data. Control of the system is carried out in digital form with 13-bit D/A converters at the outputs and A/D converters at the analog inputs. The raster scan is generated in digital form, and the pattern information is synchronized with it. The desired writing address and table address are combined digitally to generate the deflection compensation information and to drive the table servo system.

Recently ETEC Corp., Hayward, Calif., bought a permit from BTL to build a commercial system similar to the electron-beam exposure system. The ETEC system will have an ETEC electron optical column that will operate with an exposure time of 50 nanoseconds for each spot, a modulation frequency of 20 megahertz, and an electron spot diameter (address structure) of 0.20 μm. This will improve the resolution and speed capabilities of the system described above. (A system with these properties has already been built at BTL.) The price of the ETEC system will be about $125,000,000.

IBM, YORKTOWN HEIGHTS, N.Y. (References 19 and 28-30)

An electron-beam exposure system has been developed where the electron beam is programmed to assess sequentially basic geometric shapes such as rectangles and parallelograms. This is accomplished in a vector scan manner (rather than serially as in the above systems), and each of the basic elements is exposed by a fill-in scan.

This approach to pattern exposure has several attributes: it is time-efficient, since the electron beam is addressed only to the pattern areas that are to be exposed; it is efficient in the size of the data base required to describe the pattern; and the fidelity of the developed resist can be controlled by using a combination of several flexible techniques. Many of the system's components and functions have been automated. These include pattern registration, field-size control, fine-field adjustments, exposure rate, and workstage control. The column has an LaB_6 gun, two magnetic lenses, electrostatic blanking plates, and a double (magnetic) deflection assembly mounted inside the objective lens. The electron-gun supply is normally operated at 25,000 volts. The focused beam size ranges from 0.05 μm to several μm. Field size can range up to a nominal 4-millimeter square. The system exposes each field by serially filling in pattern cells, whose size, geometry, and sequence are determined by the off-line data processor. Fill-in is performed by line scanning a round electron probe within the boundary of each cell. Framing or spiral fill-in scan was also used to achieve adjustment of exposure inside the cells. The system is controlled by a dedicated IBM 1130 computer with a 32,000-word memory backed up by several magnetic disc packs,

each capable of storing 500,000 16-bit words. Digital data is transferred asynchronously from the computer to the pattern generator. The rate of exposure of the individual pattern cells is controlled by the scan-rate lock. Counting circuitry in the pattern generator drives two 14-bit D/A converters, one for each deflection axis. Pattern registration is performed either automatically or manually by detecting backscattered electrons from SiO_2 or Si registration marks on the substrate. Registration is on a chip-by-chip basis. The automatic registration system utilizes digital signal-enhancement techniques to improve the video signal-to-noise ratio, minimizes resist overexposure, averages mark defects, operates at the basic pattern-write speeds, and requires a minimum of computer input-output channel capability, speed, and capacity.

One of the problems observed when writing complex patterns in a resist coating is that exposure requirements at different areas of the pattern can differ, depending on pattern geometries and packing densities (References 28 and 30). The main reasons for this variation are that exposure is due to primary electrons of the incident beam and electrons that are backscattered from the substrate. The backscattered electrons can emerge over a relatively large region and can, therefore, affect exposure areas some distance away from the point of beam incident, giving rise to the effect generally known as "proximity effect." An effective way of solving this problem is to selectively vary the scanning speed of the beam according to exposure requirements. During vector-scan write, a convenient way to adjust for the exposure dosage is to vary the speed of the fill-in scan of each of the basic pattern elements; this is done automatically by a computer-controlled digital clock.

A 1.6- by 1.1-millimeter, 8,000 bit, field-effect transistor was fabricated with minimum line width of 1.0 μm; overall registration better than 0.25 μm was achieved.

IBM, HOPEWELL JUNCTION, N.Y. (References 31 and 32)

An electron optical system for microfabricating with new imaging and deflection concepts has been developed. The system was developed to overcome the limitations of exposure time and field coverage that has been found in conventional scanning systems used for microfabrication. Two new basic features are used: the beam-shaping concept and a projection lens with central deflection yoke (Reference 31). A square beam is used instead of a Gaussian round beam. In this system a conventional electron source illuminates a square aperture that acts as a demagnification object and is projected on the substrate, unlike SEM-type systems where the crossover is demagnified. The approach represents combined scanning and projection techniques without losing flexibility in pattern generation. A complex automatic probe stabilization method that does not interface with system operation was developed (Reference 32). A 1.25- by 1.25-μm square spot was achieved with a 0.25-μm edge resolution, corresponding to 20,000 lines per field.

MULLARD RESEARCH LABORATORIES, ENGLAND (References 33-35)

A computer-controlled electron-beam pattern generator has been developed, primarily for mask fabrication, for either conventional photolithography or, more specifically, for making masks for use in an electron image projection system developed in the same laboratories. The machine has a focused beam with a nominal diameter of 0.25 μm and is unusual in that a two-stage beam deflection system is employed to enable very finely detailed patterns to be drawn at high speed All patterns are divided into rectangular elements up to 32 by 32 μm, and these are drawn at a maximum stepping rate of 10 megahertz by an autonomous rectangle generator which has its own 8-bit D/A converters, deflection amplifiers, and coils. The rectangular elements are filled in by moving the electron beam in a decreasing rectangular spiral path. The rectangular elements are positioned accurately within a full 2- by 2-μm field by the main deflection system (15-bit D/A converters), which is addressed directly by the computer. The rectangle generator fills in the rectangular elements at high speed with good resolution but has limited range, so noise and stability problems are not serious; the main deflection system is accurate and stable but does not need a very rapid response. The beam is automatically repositioned and refocused using an array of markers predeposited on the target substrate. Automatic registration is accomplished by using a signal of backscattered electrons. An accuracy of 0.125 μm is achieved, relative to the array of markers. Patterns larger than 2 by 2 millimeters can be built up. But the major limitation of the machine is that the array of markers needed for beam registration and focusing must provide interruption for the larger pattern, as spaces must be left for more markers. A sophisticated machine is presently under consideration in which this limitation is removed. The new machine will have a laser interferometer to measure the position of the substrate to an accuracy of ±0.2 μm so that large patterns will be able to be built up without the use of closely spaced markers. With the current system, a mechanical stage for the substrate enables a 50- by 50-millimeter array of patterns to be built up. A complete mask containing details as small as 1.0 μm takes 1 to 3 hours to draw.

TEXAS INSTRUMENTS, DALLAS (References 36 and 37)

Fully computer-controlled electron-beam pattern generators with a wide field electron-optical deflection system and fully automated pattern registration system have been developed. The scan area is up to 3 millimeters square; spot diameter is variable from 0.1 to 2.0 μm; pattern distortion is 1.0 μm over a 0.25-millimeter-square field. Pattern registration accuracy is ±0.2 μm, and x-y table movement is 3 by 3 inches (76.2 millimeters). A double-deflection system was designed by computing electron trajectories through the field of the deflection coils Rectangular saddle-shaped coils were chosen since the field distortion could be easily determined and the coils could be fabricated with a high degree of accuracy Automatic pattern registration is accomplished by scanning the electron beam across reference marks on the silicone wafer, detecting and amplifying the secondary and backscattered electrons with a video amplifier, and processing this video signal to determine the correct position for the subsequently

exposed pattern. Microwave transistors were fabricated with a minimum line width of 0.5 μm.

THOMSON, C.S.F., FRANCE (References 20 and 38)

A computer-controlled electron-beam pattern generator has been developed to produce 2-inch (50.8-millimeter) masks or to expose patterns with 0.1-μm accuracy directly on a silicone wafer. During the exposure a table supporting the substrate is moved. Table motion is governed by the automatic positioning control according to a movement program specified by a Varian 620/I computer. Table position is measured to a precision of 0.04 μm by two laser interferometers; the table is moved by two stepping motors until the difference between the measured position and the position specified by the computer is less than 5 μm. Once the motors stop, the beam is tilted by position correction coils by an amount equal to the remaining error. The exposure is done by writing elementary shapes: rectangles, parallelograms, and triangles, until all the pattern is written. The alignment is done by observing the two alignment marks made during the previous exposure, by using the system as a conventional SEM. An operator determines the coordinates of the marks and enters this data into the computer. Only two marks are required to align the entire wafer.

RADIANT ENERGY SYSTEMS, NEWBURY PARK, CALIF. (References 39 and 40)

A computer-controlled electron beam scanning system for generating mask patterns has been designed. The system can be used to generate both high-resolution chromium masks for conventional processing and electron masks used in electron projection systems. This system uses a field emission electron source rather than a tungsten thermionic emitter or LaB_6 cathode. A Coates and Welter field emission gun was modified for use in the system. The spot size is 0.25 μm, and the scan field area is relatively large, 5 by 5 millimeters. For this scan area, the working distance required for a field emission system is only about 100 millimeters due to the smaller working aperture used. Field emission cathodes have intrinsically very high brightness levels with very long lifetimes (better than LaB_6). The field emission system can scan larger areas without appreciable defocusing. The primary limitation in obtaining large beam currents with field emission cathodes is emission instabilities. The field emission system requires no iron core magnetic lenses, and therefore deflection sitting times are an order of magnitude faster than with LaB_6 cathodes. The field emission system is hysteresis-free and requires no dynamic focusing over large scan fields. Single deflection coils in the field emission system reduce the design constrains required to achieve aberration-free deflection over large scan angles. The exposure and registration is done on a chip-by-chip basis using an x-y table that can move in 5-millimeter segments over a 3- by 3-inch (76.2-millimeter) mask.

BELL-NORTHERN RESEARCH, OTTOWA (Reference 41)

A system using an Advanced Metals Research 900 SEM and a Nuclear Data 812 computer has been developed. Patterns are generated utilizing a matrix of 4,096 by 4,096 randomly addressable data points. The system has been designed to patch together larger circuit patterns by breaking them up into several subfields. They are then exposed separately using mechanical stage motion to reposition the subfields. The same mechanical stage is used for the step-and-repeat operation of the complete pattern array over a 3- by 3-inch (76.2-millimeter) area. A laser interferometer is used to determine the exact location of the stage. Feedback from the interferometer is used to compensate for positional stage errors, thus ensuring the correct alignment of mask levels and the continuity of figures broken up during the patching operation. The system was designed primarily for mask generation. Pattern information is stored in the computer in terms of simple geometrical figures, such as squares, rectangles, quadrilaterals, triangles, circles, and rings.

WESTINGHOUSE RESEARCH LABORATORIES, PITTSBURGH (Reference 42)

A pattern generator that was developed consists of a fairly conventional SEM adapted for digital control. The pattern generator may be used either for exposing patterns for prototype devices directly on the device substrate, or for making electron masks for an electron-projection system. The system uses a 4,096 by 4,096 address field measuring 2 by 2 millimeters. Registration is obtained through an alignment procedure that utilizes SEM viewing of small cross-shaped alignment marks placed along the four edges of the exposure field.

JAPAN ELECTRON OPTIC LABORATORY, JAPAN (References 14 and 15)

This laboratory was one of the first that published a report about the development of a computer-controlled electron-beam exposure system for microfabrication use. The optimum scan-field area in this system is 2 by 2 millimeters. To expose larger areas, a step-and-repeat method is used in which a mechanical shift of the substrate is used. Pattern positioning is done automatically with the computer that is included in the system. Information conveyed by backscattered electrons from the wafer surface is utilized as a signal to detect the wafer locus and automatically correct any x and y directional and rotational errors.

GENERAL RESEARCH LABORATORY, JAPAN (References 43 and 44)

The electron beam system developed by this laboratory is computer-controlled. Electromagnetic lenses focus the beam into a spot smaller than 0.1 μm in diameter, over a scanning area 300 μm square.

The electron beam is deflected in two scanning modes: a raster mode used as an SEM, and a random positioning mode used as a pattern generator that is connected to a digital computer.

CAMBRIDGE SCIENTIFIC INSTRUMENT COMPANY, ENGLAND (References 45 and 46)

This system is a computer-controlled electron beam machine automated for fabricating microcircuits. The pattern stored in the computer is divided into rectangles. The electron beam scans only where exposure is needed. The basic pattern is defined by a 12-bit matrix. If the pattern requires a higher resolution than can be achieved with a single 12-bit matrix field, the pattern can be generated as a composite of subfields, each defined by a 12-bit matrix. Each complete field is assessed by a mechanical work stage movement, which allows the patterns to be repeated over the entire substrate. In a recent company catalog (Reference 46), two systems and their main features are described. One system is a research-oriented machine with a work stage movement of 75 by 75 millimeters and manual registration. The other system is for manufacturing high-resolution mask plates and for direct fabrication with an interferometer-controlled workage range of 100 by 100 millimeters. A system of the later type was bought by Rockwell International, Calif.

ETEC COMPANY, HAYWARD, CALIF. (References 47 and 48)

A computer-controlled electron beam microfabrication system was designed specifically for research and development purposes. The system is capable of generating fine resolution patterns directly on silicone wafers or generating chrome masks on 10X reticles. The approach adopted in this system is one using a series of building blocks in the form of the required modules. The travel range of the work table is 50 by 50 millimeters; it is controlled by a laser interferometer. The registration accuracy is 0.1 μm, with electronic alignment to a fiduciary mark. Spot diameter of the electron beam is 0.25 μm, with an exposure speed of 20 megahertz (Reference 30). The company offers an electron beam exposure system similar to that mentioned in the discussion of the Bell Telephone Laboratories.

CAMBRIDGE UNIVERSITY, ENGLAND (References 49-53)

A digital pattern generator (David Mann Co. pattern generator) was coupled to an electron probe instrument and used to fabricate submicrometer structures on a silicone wafer. The pattern generator has a working field of 1,024 by 1,024 points. Patterns defined within these limits are divided into small rectangular elements, the coordinates of which are punched onto paper tape. These develop appropriate scanning waveforms that control the deflection of the electron probe to expose the resist with the

desired patterns. The performance of the equipment enables line widths of 0.3 μm to be defined over a 0.1- by 0.1-millimeter field, or line widths of 0.6 μm over a 0.2- by 0.2-millimeter. The resolution within these fields is limited by the pattern generator. However, a subsidiary deflection system was used to increase the total area covered by the electrical deflection of the electron probe by a factor of 10. Alignment is performed with the aid of specially defined marks in unused areas of the working field. The electron probe is scanned over a mark, and its position is detected by means of secondary electrons. Alignment inaccuracies were found to be less than 0.2 μm.

Nixon and Owen (References 51-53) developed a low-aberration magnetic deflection system that enabled the working field to be increased. A post-lens single-deflection system was used instead of a pre-lens double-deflection system usually used in a conventional probe-forming system. The design philosophy adopted was to choose a coil geometry that gives extremely small values of the uncorrective aberration coefficients (anisotropic astigmatism and coma). It is then only necessary to correct dynamically for field curvature (isotropic astigmatism was found to be negligible). A combined electrical and mechanical method was used to align the deflection coil. A better performance was shown with the new type of deflection system.

UNIVERSITY OF CALIFORNIA, BERKELEY (Reference 54)

An SEM was interfaced with an IBM 1800 computer through a remote-access terminal. The terminal can be used to call programs stored on a disc file in the computer, to change an experimental parameter as a series of experiments progresses, and to verify changes *via* a message CRT. The system is capable of processing images produced by the SEM as well as directly recording and processing quantitative solid-state experiments. To expose a resist pattern, the operator mounts the sample in the SEM, focuses the beam, and measures the beam current and voltage. These and other measured or specified parameters are entered into the computer, which then displays the data on the CRT for verification.

CORNELL UNIVERSITY, ITHACA, N.Y. (Reference 55)

A low-cost, high-performance, digitally driven SEM system was developed. The low cost of the system was achieved by designing the digital-drive mechanism around a programmable desk calculator with expanded cassette or disc memory. In this system a hybrid A/D technique is used to generate lines. End-point data for lines is specified digitally; a continuous line is generated between the end points at a constant writing speed. In addition to lines of rectangular geometry, circles, triangles, and other shapes can also be generated. Between the calculator and its peripheral units and the SEM were added several logic hardware units consisting of a vector generator logic interface, storage unit, and the area fill-in generator.

ELECTRON IMAGING SYSTEMS

A scanning electron beam exposure system is valuable for fabricating masks and developing prototype circuits, but since it is sequential in operation, it is too slow to be of value for the production exposure of the devices themselves. In the production part, it is efficient to use an electron-beam exposure system that involves electron imaging rather than scanning. Most of the electron image projection systems that have been developed are imaged to form simultaneously a complete pattern over the entire wafer. One type of projection system uses masks coated with photocathode material (generated by a scanning system). Ultraviolet light illuminates the photocathode layer in the transport regions of the mask, causing a patterned emission of electrons from the photocathode. These electrons are imaged (one-to-one imaging) by uniform coaxial electrostatic and magnetic fields onto the facing resist-coated substrate. A second type of projection system involves the use of a focused beam that is caused to pass through a transmission mask so as to create a demagnified image of the mask on the substrate. A step-and-repeat electron projection system has been developed utilizing this method of operation. All types of projection systems mentioned above are fundamentally capable of submicrometer resolution over the full wafer area. However, nonuniform fields, imperfect substrate flatness, and field alignment errors can cause poor resolution and nonreproducible distortion (References 56-58).

In the one-to-one imaging systems photocathodes made of palladium (Pd) or cesium iodide (CsI) are slowly contaminated and must be renewed after approximately 30 to 100 exposures.

Realignment is difficult in these systems because the secondary electrons used in a scanning-beam system are trapped by the high electric and magnetic fields, and so none escape to a detector; fluorescence cannot be used because of the high level of ultraviolet light. Solutions to these problems will be described later.

The paragraphs that follow constitute a review of the electron imaging systems that have been reported.

WESTINGHOUSE RESEARCH LABORATORIES, PITTSBURGH (References 43, 59, and 60)

A one-to-one electron imaging system was first developed at these laboratories. The system is based on the electron image-tube principle, the tube itself being extremely simple. Photoelectrons emitted by ultraviolet excitation at the photocathode are accelerated to the anode by a 10,000-V/cm electric field. At the anode they are brought into focus by an axial magnetic field of approximately 1,000 gauss. The pattern projected exists in contact with a photoemissive layer and is much like a conventional photomask. The resolution attainable in the magnetically focused image is high, due to the large ratio between the final and initial energies of the electrons crossing from cathode to anode. The combination of a low-pressure mercury lamp ultraviolet source (2536 Å), a Pd photocathode, and

10,000 volts across the 10-millimeter anode-to-cathode gap, provides a submicrometer resolution capability and a depth of field of better than 100 μm. The electrodes are 60 millimeters in diameter, and by suitable shaping of the edges of the electrode, the electric field can be maintained sufficiently uniform out to 50 millimeters in diameter.

The axial magnetic field is provided by a solenoid consisting of three independently powered coils. Currents to the coils can be controlled in such a way as to orient adjustment of the image while maintaining focus and unity magnification. Simple deflection coils, providing uniform transverse magnetic fields, allow the position of the image to be adjusted over a considerable range with no loss of focus or the introduction of any appreciable distortion. All elements in the system, including the photocathode surface, are air-stable so that the tube can be repeatedly opened for loading and unloading the substrate.

The opaque parts of the mask are of titanium dioxide (TiO_2), which is formed by oxidation of a thin layer of titanium metal evaporated onto a quartz glass. The pattern is defined by a scanning electron beam exposure system (Reference 46); then a Pd layer is evaporated over the mask. Because of the nature of the cathode sensitivity effect, it is necessary to replace the Pd layer after approximately every 40 exposures. But the technique being used to fabricate the mask allows the Pd layer to be removed by etching and replaced by evaporation without affecting the permanent, hard, etch-resistant TiO_2 pattern. In this sense, the mask itself has definite life. Most of the expense of the cathode-mask is invested in the pattern generation step; consequently, renewal of the photocathode involves only the relatively inexpensive redeposition of the photoemissive layer itself.

An automatic alignment control, in which an electron-beam-induced conductivity device signal in a servo loop effects automatic correction of image position, rotation, and scale, was developed for the system. The principle of the alignment method is as follows. The cathode pattern contains two alignment marks at the opposite ends of a wafer diameter, so that the beam emanating from these marks is focused on the wafer near its periphery. On the wafer there are two corresponding beam detectors that are steps in the oxide produced by the normal planar process. A metal pad over such a step forms a metal-oxide semiconductor-type sandwich so that if a bias is applied, current will flow in the circuit due to conductivity induced in the oxide by the electron beam. When the beam is positioned on a region of thinner oxide, the current increases. Quite small changes in oxide thickness can be detected in this way. The alignment time is short compared to the exposure time. This is an advantage, since no shading of the pattern area of the cathode from the ultraviolet light need be incorporated during the alignment. The whole cathode area is illuminated by ultraviolet light, and the small integrated amount of electron irradiation of the resist on the main area of the wafer during the alignment time does not cause any significant exposure of the resist in unwanted areas.

MULLARD RESEARCH LABORATORIES, ENGLAND (References 61 and 62)

An electron image projector capable of reproducing patterns with 0.5-μm geometry over a 50-millimeter slice has been developed.

There are three developments in this particular system: (1) the design of a high-homogeneity air-core magnet that makes access to the working area easy; (2) the CsI photocathode, which simplifies operation and reduces cycle time to less than 3 minutes; and (3) the X-ray alignment method (Fay, Reference 63), which has been improved by the use of solid-state detectors and a new method of signal extraction.

CsI photocathodes with a mercury (Hg) line of 1849 Å have been found to be superior in most respects to Pd photocathodes with an Hg line of 2536 Å. They are easier to fabricate and remove than CsI cathodes; the energy of the emitted electrons is lower, so higher resolution can be achieved; current stability is higher; vacuum conditions required are mild; and the number of exposures per CsI layer is larger than with Pd cathodes. The main disadvantage of CsI is that it is very hygroscopic, and the structure of a photocathode layer is spoiled by exposure to air with a humidity greater than about 60%. However, this disadvantage is more than outweighed by the stability of emission and the simplicity of preparation and removal.

The principle of soft X-ray alignment is as follows. A marker is defined on an Si slice by some heavy metal, usually tantalum (Ta). On each mask there is an alignment area with the same pattern. During the alignment sequence, the electrons from the marker area on the mask strike the marker area on the slice. If the two patterns are misaligned, some of the electrons will strike the heavy metal, and the X-ray signal that is emitted will be at a maximum. To improve the signal-to-noise ratio, a phase-sensitive detection method is used. Automatic alignment is carried out by electronics. This method of X-ray alignment permits fine and coarse markers to be used so that optical prealignment is unnecessary.

THOMSON, C. S. F., FRANCE (Reference 63)

An electron projection system has been developed where a focusing magnetic field has a homogeneity of better than 10^{-4} over a 2-inch (50.8-millimeter) diameter. Alignment is achieved by mechanically displacing the master mask relative to the wafer, through the use of piezoelectric transducers. These act in three directions to provide x, y, and θ corrections. The alignment signal is an X-ray signal produced from a permanent alignment mark made of TaO_2 deposited on the wafer. The X-ray signal is detected through the 200- to 250-μm-thick wafer with a gas-flow proportional counter. A standard nuclear instrument chain provides a digital and analog display of the detector signal. An alignment accuracy of 0.2 μm can be obtained.

RADIANT ENERGY SYSTEMS, NEWBURY PARK, CALIF. (References 40 and 64)

This system uses a Pd photocathode. The system, in principle, is similar to the systems mentioned above, but the alignment procedure is different. Two holes in the wafer, each 250 μm in diameter, are

used as markers. These holes detect the primary beam current that reaches the rear side of the wafer from alignment marks in the photocathode. The alignment is so designed that it produces the maximum amplitude signal when it is centered about the wafer holes. A computer-controlled scan pattern first locates the holes and then scans successively smaller patterns, recalculating the center each time until an optimum alignment is attained. Total alignment time is approximately 1 second; the system detects and corrects alignment errors as small as 0.2 μm. In this technique, hole size is not critical, nor is it important whether it grows or shrinks during the processing step, as long as it changes uniformly. A disadvantage of the method is that it is difficult to keep the holes free of resist and dirt (Reference 62). The holes are produced by an air abrasive drill.

STANFORD RESEARCH INSTITUTE, MENLO PARK, CALIF. (Reference 65)

Image projection systems were designed using two-dimensional (axially symmetric) aperture lenses of both the single and multiaperture (fly's eye) kind, and one-dimensional (planar symmetric) aperture lenses. The systems were developed for use in fabricating arrays of thin-film field emitters, electron-beam-addressed memory planes, optical waveguides, and interdigital transducers for surface acoustic devices. All of these devices do not require registration of successive masks, so no attempt was made for making a registration procedure. Basically, the image projection system is based on projecting a highly demagnified electron image or pattern on a mask at the substrate plane.

An operation mode was suggested that combines the versatility of scanning exposure system with the speed and multiple imaging capabilities of a projection system. The principle is to use a single aperture as a transmission object mask and to employ electronic deflection to shift the virtual position of the object aperture in its plane. The desired object pattern is traced sequentially and thereby simultaneously forms multiple demagnified images, through a screen lens, on the substrate. This is a step-and-repeat electron projection system that does not use a stepping table but uses a screen lens.

IBM, YORKTOWN HEIGHTS, N.Y. (Reference 66)

A step-and-repeat electron projection system, analogous to the optical step-and-repeat projection system, has been developed.

In this system a mask is illuminated by a 20,000-volt LaB_6 electron gun. The mask consists of a 30- by 30-μm, 5-μm-thick, self-supporting metal foil that contains opening as small as 2.5 by 2.5 μm in a matrix appropriate to the circuit pattern. Electrons passing through the mask openings are then imaged by two magnetic projection lenses, with a 10X reduction in size, onto a wafer plane to give a 3- by 3-millimeter chip. The wafer is located on an x-y table that is stepped between exposures. The system is capable of printing 1.44×10^6 square elements of 0.25 by 0.25 μm in 0.1 second. Each of these elements is resolved at its edge to an accuracy of 0.05 μm. Novel electron-optical features required to

realize this performance are the design of an electron-optical system capable of high resolution over a large field with low distortion, the design of a condenser system for irradiating a large mask uniformly with electrons, and a method for self-focusing and mask registration.

WEST GERMANY (References 67 and 68)

This electron projection system involves the use of a focused beam that is caused to pass through a *transmission self-supporting mask on the substrate. The system is capable of generating as many as* 10,000 lines per frame at a resolution as small as 0.1 μm. It consists of a weak, long magnetic lens and a strong, short magnetic lens. The mask position excitations of the lenses are chosen so that the isotropic and the anisotropic chromatic field aberrations vanish together with third-order isotropic and anisotropic astigmatism. Practically, this step-and-repeat kind of electron projection system is designed so the demagnified image is distortion-free.

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